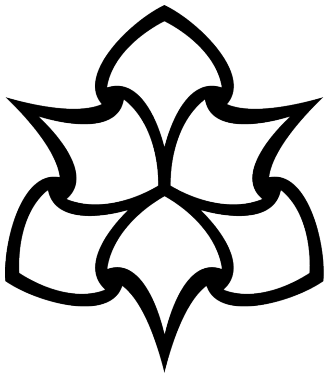

# The relationship between natural outdoor environments and cognitive functioning and its mediators

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17 Title

18 The relationship between natural outdoor environments and cognitive functioning and its mediators

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COMPETING FINANCIAL INTERESTS DECLARATION

The authors declare they have no actual or potential competing financial interests.

ABSTRACT

Background

Urban residents may experience cognitive fatigue and little opportunity for mental restoration due to a lack of access to nature. Natural outdoor environments (NOE) are thought to be beneficial for cognitive functioning, but underlying mechanisms are not clear.

Objectives

To investigate the long-term association between NOE and cognitive function, and its potential mediators.

Methods

This cross-sectional study was based on adult participants of the Positive Health Effects of the Natural Outdoor Environment in Typical Populations in Different Regions in Europe (PHENOTYPE) project. Data were collected in Barcelona, Spain; Doetinchem, the Netherlands; and Stoke-on-Trent, United Kingdom. We assessed residential distance to NOE, residential surrounding greenness, perceived amount of neighborhood NOE, and engagement with NOE. Cognitive function was assessed with the Color Trails Test (CTT). Mediation analysis was undertaken following Baron and Kenny.

Results

Each 100m increase in residential distance to NOE was associated with a longer CTT completion time of 1.50% (95% CI 0.13, 2.89). No associations were found for other NOE indicators and cognitive function. Neighborhood social cohesion was (marginally) significantly associated with both residential distance to NOE and CTT completion time, but no evidence for mediation was found. Nor were there indications for mediation by physical activity, social interaction with neighbors, loneliness, mental health, air pollution worries, or noise annoyance.

Conclusions

Our findings provide some indication that proximity to nature may benefit cognitive function. We could not establish which mechanisms may explain this relationship.

Keywords: Natural outdoor environments; green space; cognition; mediation; environmental epidemiology; built environment

## INTRODUCTION

Natural outdoor environments (NOE) are places with natural ('green and blue') elements such as parks, forests, and recreation areas. Contact with natural outdoor environments has been suggested to be beneficial to human health and wellbeing [1]. However, a large proportion of the world's population currently lives in urban areas, where they are often deprived of contact with nature. One particular concern of city living is that residents may experience more stress than rural residents [2,3], making them more vulnerable to developing mental illnesses [4]. Urban environments contain many stimuli that require directed attention due to, for example, traffic and crowding. Directed attention refers to the effortful, conscious attention for focusing on specific stimuli, while avoiding distractions. As a result, urban residents may experience more cognitive fatigue and little opportunity for mental restoration [5].

The attention restoration theory (ART) proposes that directed attention, i.e. attention directed by cognitive control processes, is restored by interaction with nature. Natural environments are thought to have minimum requirements for directed attention, allowing for directed attention functions to restore [6]. According to another theory, the stress reduction theory (SRT), nature helps to decrease stress by lowering states of arousal and negative thoughts. Natural places with certain characteristics (e.g. visible horizons for spotting of predators, availability of food) are from an evolutionary perspective better for survival, and may automatically evoke positive responses [7].

Evidence for a relation between NOE and improved cognitive function mainly originates from experimental studies typically focusing on short-term exposures (for a review, see [5]). Studies have observed improvements in memory capacity and attention after walking in natural environments, compared to walking in urban environments [8–12]. Other studies have evaluated visibility of NOE and relations with cognition; it has been found that people with a window facing a green space reported less concentration problems than those without a green view [13], and that people were less likely to be forgetful and disorganized [14]. Similarly, students with the most natural window view had better directed attention than those with built or concrete window views [15]. Even viewing pictures of natural environments resulted in improved scores on attention tests [8,16]. Other observational studies evaluating the beneficial effects of access to NOE on cognition have for example focused on working memory and behavioral development in children [17,18] and on cognitive function and dementia in older adults [19,20]. A recent review summarizing these studies reported that the number of available studies are limited and concluded that current evidence for such an association is inadequate [21].

While most of the previous research focused on cognition benefits associated with NOE visibility, more indirect pathways may also be relevant to explore. Access to NOE may affect cognition indirectly by encouraging physical activity [22], facilitating social interaction [23], and by improving mood [24], which may all be beneficial for cognitive function [25,26]. Conversely, in environments with little nature, residents may be increasingly exposed to air pollution [27] and traffic noise [28]. The exposure to air pollutants and noise and related worries and annoyance may influence cognitive functions [29–32].

There is, however, little evidence of the mechanisms underlying the relation between cognitive function and NOE. Evidence about the duration of these effects and its causality is also lacking. Another unresolved question is what type of interaction with NOE is needed for beneficial cognition effects. While most previous observational studies focused on residential distance to nature or surrounding greenness, the actual engagement with and perceived amount of nature in ones surroundings may also be important [33].

To gain further insight into the relation between long-term exposure to nature and cognitive function, we investigated the association between multiple NOE indicators and performance on the Color Trails Test (CTT), which assesses attention and executive function. We also evaluated the potential mediating roles of physical activity, social interaction, mental health, air pollution worries, and noise annoyance.

## METHODS

### *Study design and participants*

The study was undertaken within the Positive Health Effects of the Natural Outdoor environment in Typical Populations in different regions in Europe (PHENOTYPE) project. This project was established to investigate the relationship between exposure to NOE and health and its underlying mechanisms in a sample of residents from four European cities: Barcelona (Spain); Doetinchem (the Netherlands); Kaunas (Lithuania); and Stoke-on-Trent (United Kingdom) [34]. Participants were recruited from 30 neighborhoods per city that were selected in order to have variability in access to natural outdoor environments and socioeconomic status. From these neighborhoods, a random sample of 30-35 adults aged 18-75 were invited to participate, resulting in a sample of around 1000 participants per city (response rates were 46.9% in Barcelona; 8.4% in Doetinchem; 21.3% in Kaunas; and 36.9% in Stoke-on-Trent, see further details in [35]). Data were collected alongside a face-to-face questionnaire administered at participants' residences during May-November 2013. In Kaunas (Lithuania), data were collected using a postal

149 questionnaire and for this reason the CTT (our measure of cognitive function) could not be assessed in
150 participants from Kaunas. Therefore, in the current study, only data from Barcelona, Doetinchem, and
151 Stoke-on-Trent were used. All participants provided written informed consent and study protocols were
152 approved by the local ethical committees.
153 A total of 1628 participants completed the CTT. From this sample, participants with incomplete data
154 regarding indicators of the natural environment (n=83), mediators (n=222), and covariates (n=26) were
155 excluded from the corresponding analyses, leaving between n=1493 and n=1602 participants for the current
156 analyses depending on the exposure and mediator (see Tables 2-5).
157
158 ***Characterization of the natural outdoor environment***
159 NOE were characterized with data using geographical information systems (GIS) and face-to-face
160 questionnaires [34]. Participants' residential addresses were collected and subsequently geocoded.
161 - Residential distance to NOE was based on Urban Atlas 2006 [36] (Barcelona and Stoke-On-Trent) and
162 Top10NL [37] (Doetinchem) databases. Both databases use a 1:10,000 scale and a minimum
163 represented unit of 0.25ha (Top10NL was adapted to be consistent with Urban Atlas). The Euclidean
164 distance from residences to natural spaces >1 hectare [38] was calculated for the following land use
165 categories: green urban areas (e.g. public gardens, parks) (14100), agricultural land, semi-natural areas,
166 wetlands (20000), forests (30000), water bodies (50000) [39].
167 - Residential surrounding greenness was assessed with the normalized difference vegetation index
168 (NDVI). The NDVI is a measure of level of vegetation in a certain area and was derived from satellite
169 images available from Landsat 8 at a resolution of 30 m × 30 m. We aimed to find cloud-free images
170 within the greenest season (May to September) in the relevant period for this study (2011-2013), and
171 obtained images from 16th April 2013 (Barcelona area), 21st July 2013 (The Netherlands East), and
172 21st April 2011 (Stoke-on-Trent). The NDVI is based on the fact that healthy vegetation absorbs most
173 visible light and reflects large parts of near-infrared light, while sparse vegetation reflects more visible
174 light and less near-infrared light. Based on this distinction and excluding large water bodies, a value
175 between -1 and +1 was calculated, with higher values indicating higher density of green vegetation [40].
176 The average NDVI values were calculated within (Euclidean) buffers of 100m, 300m, and 500m around
177 the residence, as was done in previous research [33,41].

- Perceived amount of neighborhood NOE was assessed with questions 'How would you describe your a) neighborhood, b) street c) window view in terms of green or blue space' with answers on a five-point scale ranging from 'not at all' (1) to 'very' (5). With these questions a sum score of a, b and c questions was calculated with higher scores indicating a higher degree of nature in the neighborhood.
- Visits to NOE was assessed with questions 'How often did you visit a green or blue space in the last 4 weeks on purpose a) near your home, b) in your city, c) close to your city' with answers on a five-point scale ranging from 'never' (1) to '(almost) daily' (5).
- Total time spent visiting NOE was calculated by combining data on the number of visits to NOE (see above) with questions: 'How much time did you spend in a green or blue space a) near your home, b) in your city, c) close to your city in the last four weeks', with answers on a 4-point scale ranging from <1 hours (1) to 6-10 hours (4). Middle values of each answer category for frequency (e.g. <1 times/month was coded as 0.5 times/month) were multiplied with middle values of each answer category for duration (e.g. <1 hours/month was coded as 0.5 hours/month) and summed.

***Cognitive function***

Cognitive function was assessed with the Color Trails Test (CTT). The CTT is a language- and culture-free neuropsychological test that measures visual attention, and effortful executive processing abilities [42]. The test consists of numbered coloured circles from 1 to 25 in pink and yellow. Participants are required to rapidly connect the circles in sequence, but to alternate between the pink and yellow colors. Such a task is thought to be demanding for sustained and divided attention, and poorer CTT results have been reported in ageing populations [43] and in clinical populations with impaired cognitive function [44].

The CTT was completed at the participant's home, after the completion of the structured face-to-face questionnaire. Completion time and errors were recorded by the interviewer. Both were used as outcomes in the current study, with shorter completion time and fewer errors reflecting better cognitive function. Participants had 5 minutes to complete the test; if after 5 minutes the test was not completed, a CTT time of 300 seconds was recorded. CTT test quality was recorded by the interviewer after completion of the test. For example, if the participant had raised the pencil from the paper during the test, this was rated as 'poor quality.'

***Mediators***

- Physical activity was assessed with questions from the Short Questionnaire to Assess Health-enhancing physical activity (SQUASH) [45]. Total minutes per week of active commuting (walking and biking) and being physically active during leisure time were calculated and summed.
- Social interaction with neighbors was assessed with the question 'How often do you have contact with your neighbors?' and was scored on a 5-point scale ranging from 'at least once a week' (1) to 'seldom or never' (5), and was dichotomized into ≥1 per month and <1 per month.
- Loneliness was assessed with six statements based on the UCLA loneliness scale (e.g. feelings of isolation, feeling as part of a group of friends) [46]. Participants were asked to indicate to what extent they agreed with the statements on a 5-point scale ranging from 'totally agree' (1) to 'totally disagree' (5). A sum score was calculated with higher scores indicating greater feelings of loneliness.
- Neighborhood social cohesion was assessed with the Social Cohesion and Trust Scale, consisting of 5 items (e.g. 'people are willing to help their neighbors') [47]. Questions were scored on a 5-point scale and a sum score was calculated with higher scores indicating a higher degree of social cohesion.
- Perceived mental health was assessed with 5 questions from the Medical Outcome Study Short Form (SF-36) mental health subscale, assessing nervousness and feelings of depression in the past month. Questions were scored on a 6-point scale ranging from 'all of the time' (1) to 'none of the time' (6). A sum score was calculated and transformed into a scale ranging from 0 to 100 according to guidelines [48] with higher scores indicating better mental health.
- Traffic noise annoyance was assessed with one question about the degree of annoyance caused by traffic noise, which was scored on a scale ranging from 'not annoyed at all' (0) to 'extremely annoyed' (10) [49]. The response scale was transformed into a scale from 0 to 100, and a score of >72 was considered being highly annoyed by traffic noise [50].
- Worry about air pollution was assessed by asking to what extent participants were worried that the air pollution in their neighborhood could lead to health problems. Worries could be indicated on a scale ranging from 'not worried at all' (0) to 'extremely worried' (10). Participants were considered to be worried about air pollution when they scored >7.

***Covariates***

Covariates were chosen a priori based on previous literature [33,42,51]. Data on sex, age, educational level (primary school or no education; secondary school/ further education (up to 18 years); university degree or

higher), time spent away from home, and start date of residence at the current address were obtained from face-to-face questionnaires. Neighborhood socioeconomic status (low; intermediate; high) was based on country-specific data, and CTT test quality (good; poor) was recorded by the interviewer.

***Statistical analysis***

Descriptive statistics were calculated for the total study population and separately for each of the three cities. Parametric and non-parametric tests were used to test for significant differences between cities. To account for clustering within cities and neighborhoods, associations were analyzed with multilevel analysis with a random intercept defined at the city and neighborhood level. City-specific associations between the NOE indicators and CTT were also investigated to evaluate differences between cities.

Mediation analysis was undertaken in four steps following Baron and Kenny (1986) and previous research [33]. Conditions for mediation are that the predictor variable (NOE) must affect the mediator; and that the mediator must affect the outcome variable (CTT); and that the association between the predictor and outcome is eliminated or weakened when the mediator is included in the model.

1. The association between NOE and cognitive function. Linear and logistic multilevel models with random intercept for city and neighborhood were developed separately for CTT completion time (log transformed for normal distribution) and CTT errors (no errors/ 1 or more error(s)) as outcomes. Models were adjusted for age, sex, educational level, neighborhood socioeconomic status, time spent away from home, and CTT test quality.
2. The association between NOE and mediators. Multilevel models with random intercept for city and neighborhood were developed in which we specified the mediators physical activity, social interaction, loneliness, neighborhood social cohesion, mental health, air pollution worries, and noise annoyance as the outcome (one at a time), and indicators of NOE as the predictor. Models were adjusted for the same covariates as specified in step 1.
3. The association between mediators and cognitive function. Multilevel models with random intercept for city and neighborhood were developed in which we specified the mediators (see step 2) as predictors and the CTT as outcome. Models were adjusted for the same covariates as specified in step 1.

4. The association between NOE, mediators and cognitive function. Mediators were added to the multilevel models as specified in step 1, allowing for estimation of associations between indicators of NOE and the CTT, while adjusting for the mediators.

Finally, if the conditions for mediation were met, the proportion of the total effect mediated (i.e. the combined effect of the exposure and mediator divided by the effect of the exposure) was calculated to quantify the relative contribution of each mediator. The proportion and the 95% confidence interval were obtained through bootstrapping [33].

The analyses in step 1 were repeated while excluding participants with a poor CTT test quality (n= 38; instead of using CTT quality as a covariate) to assess robustness of our findings. We also repeated analyses in step 1 while excluding those living at their residence <1 year (n=86) to assess whether residence time affected the results.

In order to report results in a consistent manner, we calculated the percentage difference per one unit increase of the predictor for each of the estimates and 95% confidence intervals (except for CTT errors). For log-transformed outcome variables, we calculated the exponential of the coefficients and subsequently the percentage difference in the outcome per one unit increase of the independent variable: (exp(β)-1)*100 [53]. For odds ratios and coefficients for untransformed outcome variables the percentage difference was calculated as (odds ratio-1)*100 or (β/range of outcome variable)*100. All analyses were performed in STATA 14.1 [54]. Associations were considered statistically significant if the 95% confidence intervals did not include zero (β) or one (odds ratios).

## RESULTS

### *Population characteristics*

Population characteristics are presented in Table 1. Participants were on average 48 (SD=15.2) years old and 54.1% were female. Median CTT completion time varied significantly between cities and was longest in Barcelona and shortest in Doetinchem. Over a quarter (28.5%) of the participants made one or more errors on the CTT and this was similar across the three cities. The median residential distance to NOE was largest in Barcelona, and much smaller in Doetinchem and Stoke-on-Trent (p<.001). Similarly, surrounding greenness was highest in Doetinchem, followed by Stoke-on-Trent, and lowest in Barcelona (p<.001). Also the perceived amount of NOE in the neighborhood was lower in Barcelona than in the other cities (p<.001).

Furthermore, participants from Doetinchem visited NOE most often ($p<.01$) and spent most time there ($p<.05$), compared to participants from Barcelona and Stoke-on-Trent (Table 1). Correlations between objective NOE measures and the perceived amount of NOE ranged from -0.58 (residential distance to NOE) to 0.61 (residential surrounding greenness in 100m buffer). The use of NOE and objective NOE measures were less strongly correlated, we observed for example a correlation of -0.25 between residential distance to NOE and NOE visits, and 0.22 between residential surrounding greenness (100m buffer) and NOE visits (all correlations $p<.001$; Supplemental Material Table S1).

Table 1 Characteristics of study population

| | Total (n=1628) | Barcelona, Spain (n=732) | Doetinchem, the Netherlands (n=567) | Stoke-on-Trent, UK (n=329) | p value |
|---|---|---|---|---|---|
| Females, % | 54.1 | 52.3 | 57.6 | 51.8 | >.05 |
| Age, mean ± SD | 48.1 (15.2) | 44.3 (15.2) | 55.6 (12.1) | 43.6 (15.4) | <.001[a] |
| Educational level, % | | | | | <.001[b] |
| Primary school | 6.6 | 13.4 | 0.9 | 0.9 | |
| Secondary school | 45.3 | 37.6 | 44.0 | 65.1 | |
| University degree | 48.1 | 49.0 | 55.1 | 34.0 | |
| Neighborhood SES, % | | | | | <.05[c] |
| Low | 29.6 | 31.1 | 28.4 | 28.1 | |
| Medium | 35.0 | 31.7 | 39.9 | 33.8 | |
| High | 35.5 | 37.2 | 31.7 | 38.1 | |
| CTT time (s), median (IQR) | 93 ± 54 | 107 ± 54 | 83 ± 38 | 90 ± 61 | <.001[b] |
| CTT ≥1 errors, % | 28.5 | 28.3 | 27.0 | 31.8 | >.05 |
| Residential distance to NOE (m), median (IQR) | 119.6 (243.2) | 310.2 (331.1) | 45.5 (80.0) | 83.2 (106.8) | <.001[b] |
| Residential surrounding greenness, mean ± SD | | | | | |
| 100 m buffer | 0.38 ± 0.18 | 0.22 ± 0.09 | 0.54 ± 0.12 | 0.46 ± 0.08 | <.001[b] |
| 300 m buffer | 0.39 ± 0.18 | 0.23 ± 0.11 | 0.55 ± 0.09 | 0.49 ± 0.09 | <.001[b] |
| 500 m buffer | 0.40 ± 0.18 | 0.24 ± 0.11 | 0.57 ± 0.08 | 0.50 ± 0.09 | <.001[b] |
| Perceived amount of NOE, median (IQR) | 7 (6) | 5 (6) | 10 (3) | 7 (4) | <.001[b] |
| NOE total visits last 4 wks, median (IQR) | 11 (21) | 8 (19.5) | 18.5 (22) | 8 (18.5) | <.01[a] |
| NOE total time spent visiting (hours spent last 4 wks), median (IQR) | 14.0 (31.5) | 12.0 (30.5) | 18.0 (27.8) | 12.0 (44) | <.05[b] |
| Physical activity min/week, median (IQR) | 420 (580) | 240 (420) | 670 (570) | 360 (540) | <.05[b] |

| | | | | | |
|---|---|---|---|---|---|
| Social interaction neighbors <1/month, % | 9.6 | 15.4 | 3.0 | 7.6 | <.01[b] |
| Social cohesion, mean ± SD | 13.0 ± 4 | 12.0 ± 3.0 | 14.0 ± 3.1 | 13.2 ± 3.7 | <.001[b] |
| Loneliness, median (IQR) | 11 (5) | 10 (5) | 10 (4) | 13 (3.5) | <.05[d] |
| Mental health, median (IQR) | 80 (20) | 76 (20) | 84 (12) | 76 (24) | <.05[b] |
| Air pollution worries, % | 23.3 | 40.9 | 7.9 | 10.6 | <.001[e] |
| Noise annoyance, % | 14.4 | 23.1 | 6.7 | 8.2 | <.001[e] |
| Hours away from home (per week), median (IQR) | 10 (10) | 10 (11) | 11 (8) | 8 (10) | <.05[b] |

CTT: color trails test; NOE: natural outdoor environments; NDVI: normalized difference vegetation index; SD: standard deviation; IQR: interquartile range. [a] NL different from SP and UK; [b] all groups differ; [c] NL different from SP; [d] UK different from SP and NL; [e] SP different from NL and UK.

***Associations between natural outdoor environments and CTT***

Each 100m increase in residential distance to NOE was associated with a longer CTT completion time of 1.50% (95% CI 0.13, 2.89) (Table 2). No associations were found between any of the other indicators of NOE exposure and CTT completion time. No associations were found between any of the NOE indicators and CTT errors (Table 2). City-specific associations between residential distance to NOE and CTT completion time were only statistically significant for participants from Barcelona (Supplemental Material Table S2). Similar to the pooled analyses, city-specific associations between the other indicators of natural outdoor environments and CTT completion time and CTT errors were not statistically significant, with one exception: we observed a significant association between surrounding greenness (in 500 m buffer) and longer CTT completion time for participants from Doetinchem (Supplemental Material Table S2). Sensitivity analysis showed that exclusion of participants with a poor CTT test quality (n= 38) and those with time of residence <1 year (n=86) did not change the results (data not shown).

Table 2 Associations between NOE and CTT completion time and errors

| | % Difference in CTT time (95% confidence interval) | OR ≥1 CTT errors (95% confidence interval) |
|---|---|---|
| Residential distance to NOE (per 100 m) (n=1602) | 1.50 (0.13, 2.89) | 1.02 (0.97, 1.07) |
| Residential surrounding greenness 100 m buffer per IQR 0.313 (n=1602) | -0.60 (-7.27, 6.55) | 0.93 (0.74, 1.16) |
| Residential surrounding greenness 300 m buffer per IQR 0.336 (n=1602) | -0.27 (-8.59, 8.81) | 0.91 (0.72, 1.16) |

| | | |
|---|---|---|
| Residential surrounding greenness 500 m buffer per IQR 0.349 (n=1602) | -1.63 (-10.53, 8.15) | 0.89 (0.70, 1.13) |
| Perceived amount of NOE in neighborhood (n=1599) | -0.13 (-0.78, 0.51) | 1.01 (0.97, 1.05) |
| NOE visits (n=1602) | -0.04 (-0.15, 0.08) | 1.00 (1.00, 1.01) |
| NOE total time spent visiting (n=1567) | -0.01 (-0.04, 0.03) | 1.00 (1.00, 1.00) |

CTT: color trails test; NOE: natural outdoor environments; OR: odds ratio; IQR: interquartile range. Models were adjusted for age, sex, educational level, neighborhood socioeconomic status, time spent away from home, and CTT test quality and random intercepts were specified for cities (n=3) and neighborhoods (n=93).

***Associations between natural outdoor environments and potential mediators***

No statistically significant associations were observed between residential distance to NOE and any of the potential mediators (Table 3). The association between residential distance to NOE and neighborhood social cohesion was marginally statistically significant (p=0.078) (Table 3).

Table 3 Associations between residential distance to NOE and potential mediators

| | % Difference (95% confidence interval) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Physical activity (n=1526) | Social interaction neighbors (n=1602) | Social cohesion neighborhood (n=1493) | Loneliness (n=1570) | Mental health (n=1590) | Air pollution worries (n=1601) | Noise annoyance (n=1602) |
| Residential distance to NOE (per 100 m) | 1.64 (-1.30, 4.67) | -1.20 (-13.15, 12.39) | -0.60 (-1.26, 0.07) | 0.91 (-0.27, 2.11) | -0.25 (-0.71, 0.22) | 4.76 (-3.25, 13.43) | 5.08 (-4.39, 15.48) |

NOE: natural outdoor environments. Models were adjusted for age, sex, educational level, neighborhood socioeconomic status, time spent away from home, and CTT test quality, and random intercepts were specified for cities (n=3) and neighborhoods (n=93).

***Associations between potential mediators and cognitive function***

Higher loneliness and more air pollution worries were associated with longer CTT completion time, while higher social cohesion and better mental health were related to shorter CTT completion time (Table 4). Physical activity, social interaction with neighbors, and noise annoyance were not statistically significantly associated with CTT time (Table 4).

Table 4 Associations between potential mediators and CTT time

| Mediator | % Difference in CTT time |
|---|---|

| | (95% confidence interval) |
|---|---|
| Physical activity (n=1602) | 0.001 (-0.003, 0.005) |
| Social interaction neighbors (n=1602) | -4.10 (-9.78, 1.94) |
| Social cohesion neighborhood (n=1493) | -0.94 (-1.50, -0.37) |
| Loneliness (n=1570) | 1.48 (0.93, 2.04) |
| Mental health (n=1590) | -0.22 (-0.34, -0.10) |
| Air pollution worries (n=1601) | 5.43 (0.79, 10.30) |
| Noise annoyance (n=1602) | 1.02 (-4.09, 6.41) |

CTT: color trails test. Models were adjusted for age, sex, educational level, neighborhood socioeconomic status, time spent away from home, and CTT test quality and random intercepts were specified for cities (n=3) and neighborhoods (n=93).

***Associations between natural outdoor environments, mediators and cognitive function***

Finally, none of the potential mediators were significantly associated with both residential distance to NOE and CTT completion time. Since neighborhood social cohesion was (marginally) significantly associated with both residential distance to NOE and CTT completion time, we investigated the association between residential distance to NOE and CTT completion time, while adjusting for neighborhood social cohesion. However, in this model, the association between residential distance to NOE and CTT completion time increased slightly (Table 5). These results give no clear indication for mediation of the association between residential distance to NOE and cognitive function by neighborhood social cohesion.

Table 5 Associations between distance to NOE, neighborhood social cohesion and CTT time

| | % Difference in CTT time |
|---|---|
| | (95% confidence interval) |
| Residential distance to NOE (per 100 m) | 1.58 (0.19, 3.00) |
| Social cohesion neighborhood (n=1493) | -0.91 (-1.48, -0.35) |

NOE: natural outdoor environments; CTT: color trails test. Model was adjusted for age, sex, educational level, neighborhood socioeconomic status, time spent away from home, and CTT test quality and random intercepts were specified for cities (n=3) and neighborhoods (n=93).

## DISCUSSION

An increase in residential distance to NOE was related to longer completion time of the CTT. This may indicate that people living further away from nature have lower scores in cognitive function, specifically for visual attention, and effortful executive processing abilities. There were no associations between

cognitive function and (i) residential surrounding greenness, (ii) perceived amount of NOE in neighborhoods, and (iii) engagement with NOE. We found no clear indications for mediation by physical activity, social interaction with neighbors, neighborhood social cohesion, loneliness, mental health, air pollution worries, or noise annoyance.

Some of our results are in line with previous studies that also observed relations between access to NOE and cognitive function. One previous observational study that was performed in primary schoolchildren reported improvements in the development of working memory and attention after 12 months that was related to surrounding greenness in residential, school and commuting areas [17]. Another study could not find an association between proportion of parks in the neighborhood and cognitive function [19], while a UK study found surrounding greenness and private gardens to be a risk factor for cognitive impairment and dementia [20]. We are not aware of previous studies investigating the relation between access to NOE and cognitive function measured with the CTT. Most of the other previous studies had an experimental design and assessed short-term effects of exposure to nature [8,11,55]. We carried out an observational study, with subjects in their residential environments, assessing a more general, and perhaps a more sustained relation between NOE and cognitive function.

While residential distance to NOE was related to cognitive function, other indicators of NOE showed no consistent association with cognition. We found no evidence for an association between surrounding greenness, as measured with the NDVI, and cognitive function. The NDVI is relatively easy to obtain and provides a useful measure of residential greenness relevant for studies of potential cognitive benefits of natural outdoor environments. However, it's a rather coarse measure of greenness that does not differentiate between size, type and function of greenness [56].

Furthermore, we did not find an association between engagement with NOE and cognitive function. Engagement with nature may not reach its full potential for cognitive benefits when people are distracted with other things while they are in the natural space (e.g. mobile phones, crowding). Another explanation may be that especially the larger natural spaces are of importance for cognitive function, since spaces of >1 hectare were captured in the distance to natural outdoor environments indicator, while there was no such requirement in the other indicators. However, viewing nature from windows, which could include spaces

as small as a street trees, has been related to benefits for cognitive function [15,55], but we did not find such relations with our perceptions of NOE indicator which included window views. Lastly, another reason may be that the unintentional use of NOE, which was not captured in our measure of engagement with NOE, may be important for cognitive benefits, and may help explain our null findings.

We hypothesized that people living closer to nature feel less lonely, perceive higher social cohesion in their neighborhood, and have more contact with their neighbors, but could not find clear evidence for this. A Dutch study found that loneliness and shortage of social support mediated the relation between green space and health, but found no support for a mediating role of contact with neighbors [23]. They hypothesized that green spaces may be especially important for a sense of community through place attachment (i.e. the bond between individuals and places) and not because of actual contact with neighbors [23]. In a study about perceived greenness and mental health, social interaction with neighbors was not associated with mental health, while social cohesion was. It was postulated that more close social interaction than was assessed with their measure (e.g. waved, said hello, chatted) may be needed to confer health benefits [57]. Another study found that urban gardening activities were beneficial for health through social involvement and neighborhood attachment [58]. If proximity to NOE does reduce loneliness and enhance social cohesion, it might support the hypothesis that this could partially mediate cognitive performance, as perceived social isolation has been identified as a risk factor for poorer overall cognitive performance, faster cognitive decline and poorer executive functioning [59]. The increase in cognitive load from worry and chronic surveillance for threat in the environment associated with social isolation may leave fewer cognitive resources to devote to completing the CTT, but the current results do not support this and further research is needed.

We could not establish mediation by physical activity, mental health, air pollution worries, or noise annoyance. Two previous studies reported mediation of the relation between green space and general health by social cohesion, but physical activity was less important [33,51]. One explanation could be that both here and in previous studies, the mediation of physical activity in general was investigated, rather than activity in natural outdoor environments, which may have distorted the relation. Furthermore, stress may be an important mediator, since it was found to play a large role in explaining the relation between green space and health [51], and may also be relevant for the relation with cognitive function. Unfortunately, no

data on stress were available in our sample. Another analysis of the Doetinchem PHENOTYPE data revealed that the perceived sound quality (i.e. soundscape) of people's favorite NOE could contribute to perceived restoration after visiting such a place [60].

No associations were found between any of the natural outdoor environment indicators and CTT errors. While completing the CTT as fast as possible is thought to be associated with visual attention, completing the CTT without errors is thought to be associated with impulse inhibition, another function related to executive functioning [61]. Our findings might indicate that contact with nature is more related to improvements in the visual attention functions, than with impulse inhibition. However, low variability of CTT errors in our data may also be the reason for our null findings. Future research could further investigate these and other aspects of cognitive function to establish what aspects of cognition may be relevant for effects of NOE.

Our study has several strengths and limitations. Strengths are the use of a variety of objective and validated instruments for exposure, mediators, and outcome assessments; and the investigation of different study populations from three European countries using the same methodology. Cognitive function was assessed with the CTT, which is regarded to be a language- and culture-free instrument. The use of such an instrument is important considering the international nature of our study. One of the limitations includes the relatively low response rates in our study, especially for Doetinchem. Non-response analysis for the Doetinchem sample showed that respondents had less often poor general health and rated NOE to be of higher importance for physical activity and relaxation compared to non-responders [35]. This might have affected the generalizability of our study. Another limitation is the missing data for the CTT, with more tests missing in Doetinchem and Stoke-on-Trent than in Barcelona, which resulted in unequal population sizes. The cognition test was taken after the questionnaire was completed, but if this exceeded one hour, the CTT was not taken. This may have resulted in potential bias by not having cognition test scores from those participants that took longer to complete the questionnaire. However, it is unlikely that this is associated with exposure to NOE and should not have introduced bias. We did observe that associations between residential distance to NOE and CTT completion time were only statistically significant for Barcelona, the city with the largest sample size, which may have driven the significant association in the

total sample. Another reason for this result might be that the smaller amount of NOE in Barcelona makes it easier to detect associations, and when there already is a certain amount of NOE, increasing levels of NOE have little additional value. Nonetheless, we must be cautious when interpreting these results considering the possibility that our observed associations were due to chance. Although efforts were made to take into account several covariates, estimates may have residual confounding by unknown factors that could vary between study areas. Finally, with our mediation analysis we assume a certain sequence of effects, while the cross-sectional nature of our study limits us to establish the directions of these effects. This is a general limitation of cross-sectional studies and underlines the need for longitudinal studies to gain knowledge on the potential causal link between NOE and cognition and its mechanisms [21].

## CONCLUSIONS

In this cross-cultural study, we found an association between distance to NOE and CTT completion time, providing some indication that proximity to nature may benefit cognitive function, particularly visual attention. We observed no associations between other exposure indicators of NOE and cognitive function, nor could we establish mediation by physical activity, social interaction with neighbors, neighborhood social cohesion, loneliness, mental health, air pollution worries, or noise annoyance. When future research provides more evidence for an association between nature and cognition, and when more knowledge becomes available on what particular form of nature is beneficial to cognitive health and to whom, these findings could have implications for urban spatial planning policies targeted at improving access to nature in cities.

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